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Brogaard, Line Kai-Sørensen

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Technical University of Denmark

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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk

Address:	DTU Environment Department of Environmental Engineering Technical University of Denmark Miljoevej, building 113 2800 Kgs. Lyngby Denmark
Phone reception:	+45 4525 1600
Fax:	+45 4593 2850
Homepage:	http://www.env.dtu.dk
E-mail:	reception@env.dtu.dk

Printed by:	Vester Kopi August 2013
Cover:	Torben Dolin

PREFACE

The work presented in this PhD thesis was conducted at the Department of Environmental Engineering of the Technical University of Denmark (DTU) under the supervision of Professor Thomas Højlund Christensen. The work was conducted from September 2009 to June 2013. The PhD project was funded by the graduate school 3R (Residual Resources Research) at DTU Environment.

The PhD thesis is based on six scientific journal papers; of which three are published; one in second review and two manuscripts.

I Brogaard, L.K., Christensen, T.H. (2012) Quantifying capital goods for collection and transport of waste, Waste Management and Research, Volume 30, Issue 12, pp. 1243-1250

II Brogaard, L.K., Stentsøe, S., Willumsen, H.C., Christensen, T.H. (2013) Quantifying capital goods for waste landfilling, *Journal of Waste Management and Research*, Volume 31, Issue 6, pp. 585-598

III Brogaard, L.K., Riber, C., Christensen, T.H. (2013) Quantifying capital goods for waste incineration, *Journal of Waste Management*, Volume 33, Issue 6, Page 1390–1396

IV Brogaard, L.K., Petersen, P.H., Nielsen P.D., Christensen, T.H. (2013) Quantifying capital goods for biological treatment of organic waste, in review for the *Journal of Waste Management*

V Brogaard, L.K., Christensen, T.H. (2013) Life cycle assessment of capital goods for waste management systems, in manuscript for *Journal of Waste Management*

VI Brogaard, L.K., Damgaard, A., Jensen M., Barlaz, M., Christensen, T.H. (2013) Evaluation of life cycle inventory data for recycling systems, in manuscript for *Journal of Resources, Conservation and Recycling*

The papers are referred to by their roman numerals throughout the thesis (e.g. 'Paper I').

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from: DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, reception@env.dtu.dk

ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor, Thomas Højlund Christensen, for giving me the challenge of undertaking a PhD project. Thank you for good discussions, for encouraging me to work more and having high expectations of me. Thank you also for creating a great working environment made up of good and engaged people.

Special thanks go to the co-authors of the papers: Steen Stentsøe, Christian Riber, Per Haugsted Petersen, Peter Damgaard Nielsen, Morten Bang Jensen, Anders Damgaard and Morton Barlaz. I could not have completed this project without your valuable support. Thanks also to the people from ESE World, especially Björn Hedenström and Udo Frölingsdorf, who needed the results when I needed data.

Thanks to the EASETECH´ers: Anders Damgaard, Julie Clavreul, Valentina Bisinella and Alessio Boldrin. Thanks also to Torben and Lisbet for their patient and great help regarding figures. I would like to express my gratitude for informative discussions, valuable support and for keeping up good spirits to Vero, Julie, Morten, Anders, Alessio, Davide and Jacob Møller. Thanks also to the best officemate, Jacob Mønster, and to the rest of the solid waste group.

Finally, I would like to thank those who want to understand what waste management and LCA is all about, but in reality are more concerned about my happiness, health and well-being: Magnus, the big family and friends.

Summary

The life cycle assessment (LCA) of a waste management system relies on many internal characteristics such as pollution control systems and recovery efficiencies. It also relies on technical externalities supporting the waste management system in terms of capital goods and energy and material production systems. In the past, capital goods have often been disregarded because of a lack of time and assumptions of lower environmental impacts from these capital goods compared to the total impacts of waste management. However, capital goods have not been addressed in detail in the literature until now, and neglecting them may lead to an improper assessment of the environmental impacts of an entire waste management system. Another technical externality lies in the primary materials production systems required when producing secondary materials substitutes for primary materials. External databases are available today to model these primary material production processes, but their data quality varies.

The aim of this PhD project was to find the relevance and importance of technical externalities in LCA of waste management systems. To provide a thorough overview on this issue, two research questions were explored:

- How do capital goods contribute to the total environmental impacts of waste management systems?
- What are the quality and consistency of data in external databases for the primary and secondary production of materials?

Capital goods were quantified in detail for several technologies usually found in modern waste systems: a composting plant, an anaerobic digestion plant, an incinerator and landfill. As transportation and collection are important parts of waste management systems, their associated capital goods were also quantified in the terms of bins, containers and trucks.

The results from the LCAs of full waste management systems revealed that capital goods should be included in future LCAs. The impact share of capital goods was highest for resource depletion and the impacts of toxicity on humans and ecosystems.

To evaluate the quality and consistency of available data for the primary and secondary production of materials, 366 datasets were gathered. The materials in focus were: paper, newsprint, cardboard, corrugated board, glass, aluminium, steel and plastics (HDPE, LDPE, LLDPE, PET, PS, PVC). Only one quarter of these

data concerned secondary production, thus underlining a severe lack of data for these production processes.

The results showed large variations in CO_2 emissions from the production of each of the evaluated materials. An evaluation of the data revealed that energy systems are central to impacts and are thereby important to specify as background information. A critical lack of background information in external databases was highlighted as well as a lack of transparency. Therefore, the assessment of the quality of data was difficult when no description was available. Some industries and branch organisations provide data for databases, which improves the quality of the available inventories, so LCAs would represent the industry better if consensus was found in industry and branch organisations regarding the provision of data for the LCA community or if the ISO standard for producing inventory data were followed, which in turn would help to increase transparency.

In conclusion, technical externalities are important when considering the results of waste management LCAs. When technical externalities are included it is important that the background information is adequate, since the quality of the data will determine the quality of the results.

DANSK SAMMENFATNING

Livscyklusvurderinger (LCV) af affaldsbehandlingssystemer afhænger af mange interne karakteristika såsom røggasrensningssystemer eller effektiviteten af genanvendelse. Tekniske eksternaliteter understøtter og interagerer med affaldsbehandlingssystemer i form af kapitalgoder og energi- og materialeproduktionssystemer. Kapitalgoder er for eksempel maskiner og bygninger som bruges i affaldbehandlingen. Indtil nu, er kapitalgoder ofte ignoreret på grund af manglende tid til analyse og en antagelse om, lavere miljøpåvirkninger fra kapitalgoder i forhold til de samlede miljøpåvirkninger af affaldsbehandlingsssystemet. Kapitalgoder er indtil nu ikke beskrevet detaljeret i litteraturen, og det har derfor været svært for LCV udøvere at inkludere kapitalgoder i LCV af affaldsbehandlingssystemer.

En anden teknisk eksternalitet er systemet af produktion af primære materialer. Dette system ligger uden for affaldsbehandlingssystemet og disse to systemer interagerer, når sekundære materialer produceres og disse materialer erstatter primære materialer. Data i eksterne databaser er i dag tilgængelige til brug for modellering af produktion af primære materialer, men kvaliteten af data varierer.

Formålet med dette ph.d.-projekt var at finde relevansen og betydningen af de tekniske eksternaliteter i LCV af affaldsbehandling. For at give et grundigt overblik over dette blev to forskningsspørgsmål undersøgt:

- Hvordan bidrager kapitalgoder til de samlede miljøpåvirkninger fra affaldsbehandlingssystemer?
- Hvordan er kvaliteten og konsensus for data i eksterne databaser for primær og sekundær produktion af materialer?

Kapitalgoder blev detaljeret kvantificeret for teknologier som ofte bruges i moderne affaldssystemer: komposteringsanlæg, biogasanlæg, forbrændingsanlæg og losseplads. Transport og indsamling er en vigtig del af affaldssystemet, og derfor blev kapitalgoder i form af spande, containere og skraldebiler også kvantificeret.

Resultaterne af livscyklusvurderingerne af affaldssystemerne viste, at kapitalgoder bør indgå i fremtidige LCVer. Andelen af påvirkingerne var fra kapitalgoderne højest på udtømning af ressourcer og miljøpåvirkningerne toksisitet for mennesker og økosystemer.

For at vurdere kvaliteten og sammenhængen i data for primær og sekundær fremstilling af materialer, blev 366 datasæt indsamlet. Materialerne i fokus var: papir, avispapir, pap, bølgepap, glas, aluminium, stål og plast (HDPE, LDPE, LLDPE, PET, PS, PVC). Kun en fjerdedel af de indsamlede data repræsenterede sekundære materialer, og der er en alvorlig mangel på data for sekundær produktion af materialer.

Resultaterne viste store variationer i CO_2-udledningen fra produktionen af hvert af de evaluerede materialer. Denne sammenligning viste, at energisystemerne er centrale for de affødte miljøpåvirkninger, og at det derfor er meget vigtigt, at energisystemerne er beskrevet i baggrundsmaterialet for et datasæt. Mange datasæt mangler baggrundsmateriale, og det materiale, som kan findes, er ofte ikke transparent. Når der ikke er noget baggrundsmateriale, er det er svært at vurdere kvaliteten af et datasæt, og dermed om det kan bruges i en LCV. Nogle industrier og brancheorganisationer leverer data til databaser, og dette forbedrer kvaliteten af de tilgængelige datasæt. LCVer ville repræsentere industrien bedre, hvis konsensus blev fundet iblandt industri og brancheorganisationer for at levere data til LCV-samfundet. Hvis ISO-standarderne for at producere data blev fulgt, ville det bidrage til at øge gennemsigtigheden i databaserne.

Det kan konkluderes, at tekniske eksternaliteter er vigtige for resultaterne af LCV af affaldsbehandlingssystemer. Når de tekniske eksternaliteter er inkluderet, er det vigtigt, at baggrundsoplysninger er tilstrækkelige, da kvaliteten af data vil bestemme kvaliteten af resultaterne.

LIST OF CONTENTS

1 INTRODUCTION

1.1 WASTE MANAGEMENT

The first goal of waste management is to protect human health and the environment from the uncontrolled dumping of waste. The second goal is to recover resources from the waste stream, since the need for resources is increasing (European Commission, 2008).

The waste hierarchy is meeting these goals and it states the order of treatment options for waste. The least favoured option is landfilling because it only meets the first goal of protecting humans and the environment from waste. Better than landfilling is energy recovery from waste and its subsequent utilisation. Going up the hierarchy, recycling and reuse increase in importance, and the most preferred option is the prevention of waste. Research is aiming globally at optimising treatment processes, in order to recover waste in terms of materials and energy and still fulfil the first goal. The main issue with recovering materials is that the recovery processes are energy intensive, and recovering some materials will use other resources. At the same time, however, recovered materials substitute for primary materials and save virgin resources. To assess these complex systems the European Waste Framework Directive (European Commission, 2008) recommends life cycle assessment (LCA) as a tool. This is supported by the Thematic Strategy on the prevention and recycling of waste (European Commission, 2005).

LCA is a powerful decision-support tool which is used to assess environmental impacts caused by a product or a service system. Waste management is a service-providing system, and LCA can be used to assess the system as a whole and avoid pollution/damage shifting from one lifetime phase to another. LCA also helps policymakers to rank waste management options according to environmental performance. The LCA methodology is a holistic approach, ensuring that the full system is assessed.

LCA is very data-demanding, and assumptions must be made when data availability is scarce. Lack of data can be caused by time constraints or difficulties in finding data for the actual case being assessed. A common assumption in LCAs of waste management systems is that capital goods are negligible in terms of total environmental impacts (Clift et al., 2000; Frees, 2002). Capital goods in terms of buildings and machinery used in waste management systems are classed as *technical externalities* to the waste management system (Figure 1). Capital goods are the basis of the system, i.e. the goods that carry out waste treatment processes.

A few studies include capital goods in the LCA of waste management systems, but only limited data is available on this subject. Capital goods were described by Frischknecht et al. (2007), who found that impact shares were major for Mineral Resources and substantial for Land Use as a result of landfilling and incineration (Frischknecht et al., 2007). A few studies have presented life cycle inventories for capital goods in line with waste management technologies (Doka, 2009; Ecobalance, 1999; Ménard et al., 2004; Schleiss, 1999; Martinéz-Blanco et al., 2010), but the data presented are not described in detail and do not allow the reader to ascertain the amounts of materials needed for different parts of the technologies. Using data from other studies is therefore not possible.

Another assumption is that the quality of available data is sufficient. Data used for LCAs determine results, so the choice of data can be crucial. Data are needed for waste management processes and for the responding systems of energy and material production. Material systems produce primary materials, which are substituted for by secondary materials produced in the waste management system. The same can be said for the external energy system, which produces energy at the market responding to the energy recovered in the waste system. These two production systems represent the two other technical externalities to the waste management system (Figure 1).

External material production systems are presented in databases globally. Data represent the production of primary materials and can be found in both commercial and public databases.

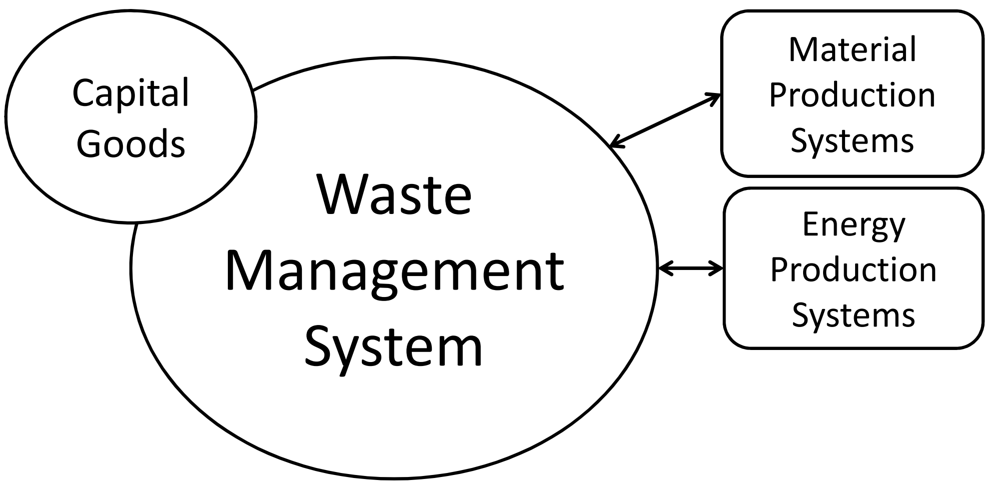

Figure 1: Waste management system and corresponding technical externalities.

Several studies (Münster and Lund, 2009; Fruergaard and Astrup, 2011; Eriksson and Bisaillon, 2011) have examined how energy systems can be described, documented and modelled in the best way, to respond to the impacts caused by waste management. These studies cover technical externalities in terms of responding energy systems and are therefore not included in this study.

1.2 Aim of the PhD project

The aim of the PhD study was twofold: 1) to verify/contradict the assumption that the environmental impacts of capital goods can be neglected. This would be achieved by quantifying, documenting and assessing impacts of capital goods: composting plants, anaerobic digestion plants, incinerators, landfill sites, bins and trucks and 2) to evaluate the quality of data for the primary and secondary production of materials in external databases. The materials under study were materials from within the municipal waste stream: paper, cardboard, corrugated board, newsprint, plastics (HDPE, LDPE, LLDPE, PET, PP, PS and PVC), glass, steel and aluminium.

1.3 Content of the PhD thesis

After the introduction to the thesis in Section 1, Section 2 presents the methods used for data collection and the development of inventories, descriptions of how life cycle inventory databases were evaluated and the background to the life cycle assessment methodology. Section 3 deals with capital goods: composting plants, anaerobic digestion plants, incinerators, landfill sites, bins and trucks. Inventories for all capital goods are presented together with their full LCAs in waste management, which then leads to a conclusion on the importance of including these elements in the LCA of waste management systems.

Section 4 discusses databases for material production and recycling, and it describes how data for the same material vary between databases and the challenges LCA practitioners meet in acquiring representative data for their studies.

The outcomes of the study are summarised and discussed in Section 5 and concluded in Section 6.

The research results presented in the PhD thesis are a summary of six scientific papers, which are enclosed as appendices.

2 METHODS

The two objectives of the study demanded different approaches. The first part – assessing capital goods – included the collection of data from consultants and within industry. The other part – data quality for recycling systems – included an evaluation of databases available to LCA practitioners. For both parts, knowledge about LCA methodologies and how to perform LCAs was required, and this is covered in the last subsection of the methods section.

2.1 DATA COLLECTION AND QUANTIFICATION

In collaboration with consultants and within the industry as a whole, data were collected regarding the design and construction of the technologies and facilities used in waste management. These two points of contact were the only information sources available, since most of the literature does not address capital goods or provide any detailed data on the subject.

Danish engineering consultants COWI and Ramboll provided most of the data, as they are responsible for building incinerators, landfills, anaerobic digestion plants and composting plants.

In collaboration with the consulting engineers, inventories were built based on their experience in designing plants, drawings of existing plants and the advice of construction experts.

Companies producing parts for waste management technologies were consulted. Some of the manufactured outputs in this respect were concrete tanks (Perstrup Concrete, 2013), steel reactors (Assentoft Silo, 2013), Volvo trucks (Jensen, 2010), gas management systems (Ammongas, 2013), PVC covers for manure tanks (Ceno Top, 2013) and bins (ESE World, 2010; Kingspan, 2010). All data sources are included in the inventory papers I-IV.

2.2 LIFE CYCLE INVENTORY DATABASES

The second part of the PhD project evaluates data on the production of primary and secondary materials in external databases. The materials included in the study were: paper, newsprint, cardboard, corrugated board, plastics (HDPE, LDPE, LLDPE, PET, PP, PS and PVC), steel, aluminium and glass.

For data gathering the following sources were used:

- Source list at ELCD's homepage (ELCD, 2013)
- Simapro (PRé, 2013) and GaBi (PE International, 2013), which include many databases, such as Ecoinvent (2013), IDEMAT (2001), PE International (2013) and U.S. Life Cycle Inventory Database (USLCI, 2013).
- Freely available data, e.g. the European reference Life Cycle Database (ELCD, 2013) and GEMIS (1990).
- Scientific papers and reports.

The full list of databases and a description of their data are presented in Section 4.

2.3 LIFE CYCLE ASSESSMENT METHODOLOGY

The EDIP methodology (environmental design of industrial products), put forward by Wenzel et al. (1997), was used for the life cycle assessments. The non-toxic impact categories assessed were as follows: Global Warming (GW), Acidification (AC), Terrestrial Eutrophication (TE), Aquatic Eutrophication in N-equivalents (AE(N)) and in P-equivalents (AE(P)), Photochemical Ozone Formation impacts on vegetation (OFv) and human health (OFh) and Resource Depletion (RD).

USEtox (Rosenbaum et al., 2008) was used to assess the following toxic impacts: Human Toxicity related to cancer (HTc), Human Toxicity non-cancer-related (HTnc) and Ecotoxicity (ET).

The time frame for the emissions was 100 years and long-term emissions were not included in the assessments.

The Simapro 7.2 (Pré, 2011) and EASETECH (Clavreul et al., 2013) LCA software packages were used for the assessments. Simapro was used for the product systems whereas EASETECH was used for waste treatment. EASETECH is a waste LCA tool, and in this project it was used for modelling the use phase of the waste management technologies.

The results are presented in person equivalents (PE), and normalisation references taken from Laurent et al. (2011a) and Laurent et al. (2011b) were employed. All normalisation references are presented in Table 1. Unit PEs represent impacts on an average person in a specific area in a reference year.

Table 1: Environmental impact categories and normalisation references used for the assessment (Laurent et al., 2011a, 2011b). UES: Unprotected Eco-System. CTU: Comparative Toxic Unit, e: Ecotoxicity, h: human.

Impact categories	Geographical scope	Normalisation references	Unit
EDIP			
Acidification	Europe	393	[m² UES/person/year]
Aquatic Eutrophication (N-equivalents)	Europe	8.32	[kg N-eq/person/year]
Aquatic Eutrophication (P-equivalents)	Europe	0.282	[kg P-eq/person/year]
Global Warming	World	7730	[kg CO2-eq/person/year]
Ozone Depletion	World	0.0205	[kg CFC-11-eq/person/year]
Photochemical Ozone Formation – impacts on human health	Europe	2.84	[m².ppm.hr/person/year]
Photochemical Ozone Formation – impacts on vegetation	Europe	59700	[m².ppm.hr/person/year]
Resource Depletion	World	0.817	[person reserves/person/year]
Terrestrial Eutrophication	Europe	1370	[m² UES/person/year]
USEtox			
Human Toxicity, cancer	Europe	0.0000325	[CTUh/person/year]
Human Toxicity, non-cancer	Europe	0.000814	[CTUh/person/year]
Ecotoxicity	Europe	5060	[CTUe/person/year]

3 CAPITAL GOODS

The waste management system has two flow systems – a capital goods flow and a waste flow. The waste flow assumes a zero-burden approach, meaning that no upstream processes are included. Waste is treated in the waste management system and output as secondary materials and recovered energy. The flow of capital goods includes material and energy production, the construction of capital goods, waste management treatment and the disposal phase, including the recycling and landfilling of the capital goods. The two flows are illustrated in Figure 2. Transportation of materials and products is part of the system between all processes. The conceptual model for presenting the potential environmental impacts from waste management systems including capital goods was presented in Paper V.

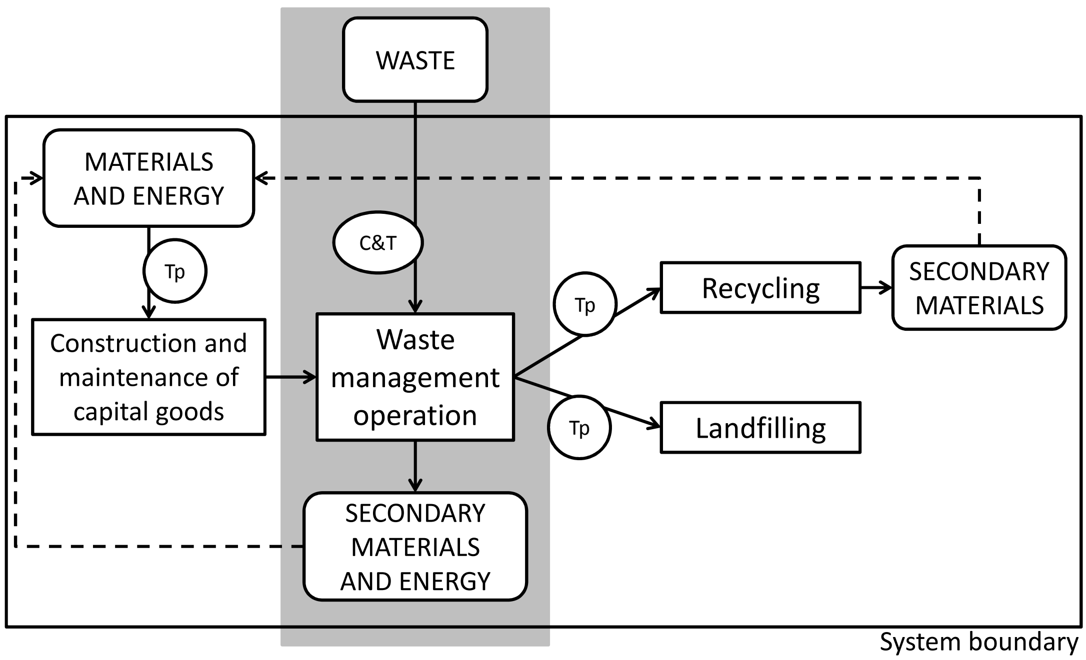

Figure 2: Flow diagrams of the life cycle assessments. Dotted lines show the system's boundaries. Secondary materials and energy are connected to the substituting production of materials and energy. Grey area shows traditional boundaries for waste management LCAs. Tp: transport.

3.1 CONCEPTUAL MODEL

The potential environmental impacts from the total waste management system (PEI) is the sum of the impacts of the two flow systems. All of the following considerations are measured per tonne of waste handled.

$$PEI = CG + W \qquad \text{(Eq.1)}$$

where:

- PEI: potential environmental impact from the total waste management system
- CG: impact from capital goods
- W: impact from the handling of waste, including recovery.

The waste system can be further decomposed as follows:

$$W = C\&T + T - m_w \cdot SM - e_w \cdot SE \qquad \text{(Eq.2)}$$

where:

- C&T: impact from collection and transport
- T: impact from the treatment of waste
- SM: impact from saved materials expressed as an impact similar to production from virgin materials
- m_w: a factor relating to the amount of virgin material production avoided against the amount of waste recycled or reused
- SE: impact from saved energy expressed as an impact similar to production from other energy sources
- e_w: a factor relating to the amount of energy production avoided per amount of waste treated by energy recovery.

The capital goods system can be decomposed further; the parentheses represent the disposal phase of the capital goods:

$$CG = E + C + (R + L + I - m \cdot SM_{R,I} - e \cdot SE_{I,L}) \qquad \text{(Eq.3)}$$

where:

- E: impact from material extraction and production (including maintenance and lifetime considerations)
- C: impact from the construction of capital goods. Transport to the site included
- R: impact from the recycling of capital goods

- L: impact from the landfilling of capital goods
- I: impact from the incineration of capital goods
- $SM_{R,I}$: impact from materials saved from the capital goods (direct recycling or after incineration) ,expressed as an impact similar to production from virgin materials
- m: a factor relating to the amount of virgin material production avoided per amount of waste treated
- $SE_{I,L}$: impact from saved energy (from incineration or landfilling) expressed as an impact similar to production from other energy sources
- e: a factor relating to the amount of energy production avoided per amount of waste treated

Equation 1 can now be decomposed into:

$$PEI =$$

$$E + C + (R + L + I - m \cdot SM_{R,I} - e \cdot SE_{I,L}) + (C\&T + T - m_w \cdot SM - e_w \cdot SE) \quad \text{(Eq.4)}$$

This equation is a conceptual and general description of the total environmental impact of the waste management system, including capital goods and the fact that parts thereof can be recovered. The significance of each term will depend heavily on the waste being considered, as capital goods depend on the waste being treated, while impacts from treatment as well as recovery depend on the actual waste.

In order to assess the significance of the capital goods in an environmental context, six scenarios were employed to address different waste types and waste management systems. The scenarios are therefore not comparable, but each one can be used to assess if the impact of capital goods is significant or insignificant. The six scenarios are:

1 - Composting of 1 tonne of garden and park waste

2 - Anaerobic digestion of 1 tonne of mixed organic waste (manure, organic waste from households and straw)

3 - Incineration of 1 tonne of residual household waste (without paper, cardboard and glass source segregated by households)

4 - Landfilling of 1 tonne of mixed waste (mixed non-sorted waste from households, including organic waste)

5 - Collection and transportation of 1 tonne of household waste

6 - Collection and transportation of 1 tonne of waste paper from public collection points.

3.2 Inventories

The inventories for the six scenarios in this section are presented per tonne of waste treated by the specific technology. A more detailed description of the construction of capital goods for all technologies can be found in Papers I-IV.

Data used for the operation of the technologies were all taken from the EASETECH database (Clavreul et al., 2013). The previous version of EASETECH is known as EASEWASTE, by Kirkeby et al. (2006).

3.2.1 Windrow composting

Organic waste from parks and gardens, food waste and sludge can be composted in open or closed systems. Closed systems are often chosen to protect neighbours from obnoxious smells. With proper handling and the frequent turning of compost in open systems, odours can be reduced.

The composting plant consists of a large concrete paved area, a number of houses for the staff and equipment and machinery for shredding, sifting, screening, sorting and turning the waste and compost.

Engineering consultants from Ramboll helped to gather the main data for the inventories for three types of waste in two different capacities (10,000 and 50,000 tonnes per year). Data for smaller quantities were found in the literature and via specialised companies (e.g. silo producers). All data can be found in Paper IV. The waste types were: garden and park waste (G&P waste), bio-waste in terms of food waste mixed with G&P waste and bio-waste in terms of sludge from waste water treatment plants.

The materials used most for the composting plant were concrete stones and gravel for pavements. The lifetime of a composting plant averages about 10 years.

Table 2 presents the inventory data per tonne of waste based on the inventories produced in Paper IV for composting 50,000 tonnes of garden waste per year. Diesel and electricity were consumed during the usage phase and the outputs were 689 kg of compost and 48 kg of wood chips per tonne of input waste. Table 2 shows the amounts of materials sent for disposal, i.e. amounts of waste from the capital goods. The disposal phase included recycling and landfilling. Not all materials were disposed, since the gravel below the concrete pavement, for instance, was not excavated and reused.

Table 2: Life cycle material data for composting one tonne of organic waste (Paper V). Reinf: Reinforcement. Mach: Machinery

Materials	Unit per tonne of waste	Excavation and production of materials	Construction	Use	Disposal
Asphalt	[t]	1.10E-03	-	-	1.10E-03
Buildings	[t]	2.30E-03	-	-	2.30E-03
Cables	[t]	9.30E-07	-	-	9.30E-07
Compost	[kg ww]	-	-	6.89E+02	-
Concrete	[t]	1.10E-03	-	-	2.20E-02
Concrete stones	[t]	2.00E-02	-	-	-
Diesel	[l]	-	-	3.00E+00	-
Electricity	[kWh]	-	-	2.00E-01	-
Gravel	[t]	9.40E-02	-	-	-
HDPE	[t]	8.30E-06	-	-	8.30E-06
Mach. steel	[t]	1.80E-04	-	-	1.80E-04
PP	[t]	1.80E-08	-	-	1.80E-08
PVC	[t]	6.20E-08	-	-	6.20E-08
Reinf. steel	[t]	7.80E-06	-	-	-
Steel	[t]	2.20E-05	-	-	2.90E-05
Transport at site	[l]	-	2.50E-03	-	-
Woodchips	[kg ww]	-	-	4.80E+01	-

3.2.2 Anaerobic digestion

The design of anaerobic digestion plants depends on the climate and the type of waste digested. These factors create large variations in the amounts of materials required, from large-scale steel tanks to small underground plants in households in developing countries. In industrialised societies large-scale plants are built with steel reactors and large concrete tanks for receiving manure.

Gathering data for the quantification of materials and energy used for the construction of anaerobic digestion plants turned out to be more difficult than expected, due to variations in plant design.

Data were gathered from a company producing reactor tanks, Assentoft Silo (2013), which provided the data for the steel reactors and outlined requirements for other tanks constructed in concrete, silos, feeding equipment, weighbridges, etc. From this information it was possible to gather data from companies manufacturing each specific product.

The anaerobic digester included: a weighbridge, receiving tanks with PVC covers, mixing tanks, a silo for energy crops, a heat exchanger for manure, reactor tanks, storage tanks for slurry, gas flares, process management, motors and gas cleaning equipment. All details regarding plant design can be found in Paper IV.

An inventory for an anaerobic digestion plant is presented per tonne of waste in Table 3. Data concerning the use phase were calculated in EASETECH (Clavreul et al., 2013) and represent a plant with a capacity of 80,000 tonnes of waste per year with a mix of food waste, manure, straw, fat and a mix of other organic waste. The types of waste define the type of receiving silos as well as the feeding equipment.

For the life cycle assessment, a mix of organic household waste, manure and straw was used as an input into the anaerobic digestion process. The composition of the organic household waste was provided in a study by Petersen and Domela (2003), which showed a composition of organic waste after source segregation of 62% vegetable food waste, 19% animal food waste, 7% garden waste and 11% other organic waste fractions. The mix of substrates was 25% food waste, 65% manure and 10% straw. The assessment did not consider any upstream processes for the manure and straw, as both substrates were considered as waste with a zero-burden approach. The share of each substrate was based on the input into the actual plant, which also represented the capital goods. A total of 220 tonnes of substrates were fed into the primary reactors every day, with a retention time of 30 days and a thermophilic process (55–60˚C). The secondary reactor tanks had an input of 220 tonnes per day, a mesophilic process (25–35˚C) and a longer retention time of 38 days.

Concrete was used the most, and together with different types of steel it was the major material found in the anaerobic digestion plant. It was not possible to quantify the energy consumption for construction due to lack of information. The transportation of goods was estimated to be of greater importance than the energy used at the site of construction.

Concrete parts (receiving tanks and a silo) had on average a shorter lifetime than steel components, so a 30-year maintenance schedule was included for these short lifetime elements. Further details about the lifetimes of the parts can be found in Paper IV.

All parts were considered disposed, with 75% going to recycling and 25% to landfill. The assumption about the disposal was made due to a lack of data about the treatment of demolition waste.

Biogas was used to produce heat and electricity at a motor running at the site. The efficiency of the motor was estimated to be high (80%), with a share of 50% heat and 30% electricity.

Table 3: Life cycle material data for the anaerobic digestion of 1 tonne of organic waste (Paper V). WEEE: Waste Electrical and Electronic Equipment. PVC: Polyvinylchloride. Reinf: Reinforcing.

Materials	Unit per tonne of waste	Excavation and production of materials	Construction	Use	Disposal
Asphalt	[t]	6.80E-04	-	-	6.80E-04
Buildings	[t]	5.10E-04	-	-	5.10E-04
Cables	[t]	1.10E-07	-	-	-
Computer units and screens	[t]	2.00E-08	-	-	-
Concrete	[t]	4.30E-03	-	-	4.30E-03
Diesel	[l]	-	-	9.00E-01	-
Electricity	[kWh]	-	-	4.90E+01	-
Foamglass	[t]	2.00E-06	-	-	2.00E-06
Insulation	[t]	1.20E-05	-	-	1.20E-05
Joint filler	[t]	1.20E-07	-	-	-
Pig Iron/Cast Iron	[t]	5.40E-06	-	-	-
PVC	[t]	4.60E-06	-	-	4.60E-06
Reinf. steel	[t]	2.60E-04	-	-	-
Sand	[t]	1.20E-04	-	-	-
Stainless steel	[t]	5.00E-06	-	-	-
Steel	[t]	1.70E-04	-	-	4.40E-04
WEEE	[t]	-	-	-	1.30E-07

3.2.3 Incineration

Incineration is an expensive technology to establish and it needs good infrastructure to ensure it runs continuously. Electricity and heat output can be used as substitutes for conventional energy. Filters and air control management procedures have been highly developed in order to clean flue gas from dioxins, particles, NOx and SO_2.

Table 4: Life cycle material data for incinerating one tonne of waste (Paper V).

Materials	Unit per tonne of waste	Excavation and production of materials	Construction	Use	Disposal
Asphalt	[t]	9.60E-05	-	-	9.60E-05
Computer units and screens	[t]	4.10E-07	-	-	-
Concrete	[t]	1.10E-02	-	-	1.10E-02
Diesel for clearing of site	[l]	-	9.50E-04	-	-
Electricity	[kWh]	-	1.10E+00	-	-
Electronics and cables	[t]	7.40E-06	-	-	-
Fiberglass	[t]	2.50E-05	-	-	2.50E-05
Glass	[t]	7.10E-06	-	-	7.10E-06
Steel (building)	[t]	9.10E-04	-	-	9.10E-04
Steel (machinery)	[t]	1.10E-03	-	-	1.10E-03
Transformer	[t]	1.40E-06	-	-	-
WEEE	[t]	-	-	-	7.80E-06

Incinerators today have similar designs with a waste bunker, a furnace with a boiler, energy recovery with a turbine and generator and flue gas treatment, either wet or semi-dry.

Data gathering for six incinerators built in Scandinavia (Finland, Norway and Denmark) between 2006 and 2012 was carried out in collaboration with Ramboll consultant engineers. Quantification included the major materials – concrete and steel – as well as glass, electronics, cables and asphalt. The plants quantified for this study had a lifetime of 30-40 years and were of different capacities, from 72,000 tonnes per year to 240,000 tonnes per year.

Table 4 gives an example of an incinerator with a capacity of 120,000 tonnes per year which incinerated residual household waste. Data concerning the use phase were obtained from the EASETECH database (Clavreul et al., 2013), and all chemicals and fuels were included in the modelling. Internal energy consumption was used from in-house production and is therefore not mentioned in Table 4. Two scenarios were assessed for the incinerators. The first scenario included the high recovery of energy from waste (95% lower heating value), representing Nordic conditions with the production of both heat (74%) and electricity (21%). The other scenario was modelled using a smaller production of heat, representing areas where there is a lower need for heat. The efficiency for the European incinerator was a 29.5% lower heating value with a share of 24% for electricity and

5.5% for heat. Capital goods for distribution networks (cables and district heating networks) were not included.

3.2.4 Landfilling

The landfilling of waste is used globally as a low-cost option for waste management. The cheapest option within landfill technologies is an open dump without any gas and leachate management, but it also has a high environmental impact. Gas management can be applied, however, where organic waste fractions are landfilled, and through proper gas management the impacts of landfilling can be reduced. Leachate collection is preferred for all kinds of landfills to save local water resources.

Consultants from the engineering consultant company COWI (2012) contributed to the data gathering process, to quantify the materials and energy used to construct a landfill site. Through close collaboration, all details for the construction were described and the types of materials used for all parts of a landfill (see detailed quantification in Paper II) were determined. The management of gas and leachate with energy recovery was included. The high efficiency (80%) of a landfill gas motor was assumed, with a share of 50% for heat and 30% for electricity production.

Clay and gravel for the liner system were used most, but they were not recyclable at the end of their life because landfills remain at site forever. Transportation *at site* and *to site* was quantified, as the large volumes and mass used would lead to the high consumption of diesel by trucks, front loaders, compactors, etc. Data for daily soil cover, diesel for spreading and compacting waste were included.

Data for the landfill operation were found in the EASETECH database (Clavreul et al., 2013). The landfill assessed was made up of 3.5 million tonnes of waste. The filling time was assumed to be 10 years with an aftercare period of 30 years. In Table 5 the inventory for the landfill is presented per tonne of waste.

Table 5: Life cycle material data for landfilling of one tonne waste (Paper V).

Materials	Unit per tonne of waste	Excavation and production of materials	Construction	Use	Disposal
Aluminium	[t]	5.80E-08	-	-	5.80E-08
Asphalt	[t]	4.20E-04	-	-	4.20E-04
Buildings	[t]	1.20E-04	-	-	1.20E-04
Cables	[t]	2.00E-07	-	-	2.00E-07
Clay	[t]	8.10E-02	-	-	
Concrete	[t]	1.00E-03	-	-	9.90E-04
Copper	[t]	9.80E-09	-	-	9.80E-09
Diesel - daily soil cover	[l]	-	-	3.20E-02	-
Diesel at site	[l]	-	1.20E-01		-
Diesel for compacting	[l]	-	-	4.70E-01	-
Gravel	[t]	1.80E-01	-	-	-
HDPE	[t]	2.30E-04	-	-	4.10E-05
Leachate management	[kWh]	-	-	8.00E-02	-
Machinery steel	[t]	5.80E-05	-	-	-
PP	[t]	4.00E-08	-	-	4.00E-08
PVC	[t]	9.60E-06	-	-	
Reinforcing steel	[t]	4.90E-05	-	-	4.90E-05
Steel	[t]	8.60E-05	-	-	1.40E-04

3.2.5 Collection and transportation

Capital goods for the collection and transportation of waste include bins, plastic and paper bags, metal rack containers, underground containers and trucks. Two types of container were described in this section, namely the 240-litre bin typically used in single family houses and a cube for the public collection of paper. More inventories for bins and containers can be found in Paper I. Both containers were made of high density polyethylene (HDPE). The 240-litre bin had a steel axle for two rubber wheels and the cube had an inner part of steel which is used when emptying. Washing the 240-litre bins with cold water was the only maintenance included. Inventories for the two containers are presented in Table 6 and Table 7.

The type of waste collected depicts the capacity of the containers, which does not vary as much for the household waste bin (1.8-2.2 tonnes/year) as for the cube (33-125 tonnes/year), since the cube can collect paper, cardboard or glass.

Trucks, which nowadays are becoming more specialised, are hybrid in nature, i.e. they operate on both electricity and diesel. Working conditions for waste collectors have also improved through the introduction of a lower entrance and a low floor for easy access to the truck. In this study a collection truck with a body of 16m^3 was included. The capacity was 1460-1750 tonnes per year and its lifetime was 12-15 years. The main material used for producing the truck was steel for the chassis and body. A few materials were not considered for the disposal phase because of a lack of data, e.g. for the treatment of car batteries. The inventory for the truck is presented in Table 8.

Table 6: Life cycle material data for a 240-litre bin (Paper V).

Materials	Unit per tonne of waste	Excavation and production of materials	Construction	Use	Disposal
Colour/paint	[t]	2.60E-06	-	-	-
Electricity	[kWh]	-	3.10E-01	-	-
HDPE	[t]	2.60E-04	-	-	2.60E-04
Lubricating oil	[t]	-	3.20E-07	-	-
Nitrogen	[t]	-	4.70E-09	-	-
Paper	[t]	-	7.00E-07	-	-
Propane	[t]	-	3.80E-08	-	-
Rubber	[t]	4.70E-05	-	-	4.70E-05
Steel	[t]	1.50E-05	-	-	1.50E-05
Water	[t]	-	2.90E-05	2.47E-03	-

Table 7: Life cycle material data for a 1.5 m^3 cube for waste paper collection (Paper V).

Materials	Unit per tonne of waste	Excavation and production of materials	Construction	Use	Disposal
Colour	[t]	5.10E-07	-	-	-
Electricity	[kWh]	-	1.60E-01	-	-
HDPE	[t]	5.10E-05	-	-	5.10E-05
Lubricating oil	[t]	-	6.20E-08	-	-
Nitrogen	[t]	-	9.10E-10	-	-
Paper	[t]	-	1.40E-07	-	-
Propane	[t]	-	7.20E-09	-	-
Steel	[t]	3.20E-05	-	-	3.20E-05
Water	[t]	-	5.50E-06	-	-

Table 8: Life cycle material data for a 16m^3 collection truck (Paper V). Diesel consumption during the use phase is presented for a scenario involving the collection of household waste from a 240-litre bin and collecting paper waste from a cube container. RHH: residual household

Materials	Unit per tonne of waste	Excavation and production of materials	Construction	Use	Disposal
Aluminium	[t]	9.20E-06	-	-	9.20E-06
Battery	[t]	6.00E-06	-	-	6.00E-06
Bitumen	[t]	2.70E-07	-	-	-
Brass	[t]	4.10E-07	-	-	4.10E-07
Colour/paint	[t]	5.90E-07	-	-	-
Cooling agent	[t]	4.60E-08	-	-	4.60E-08
Copper	[t]	6.40E-07	-	-	6.40E-07
Diesel (collecting paper waste)	[l]	-	-	4.90E+00	-
Diesel (collecting RHH waste)	[l]	-	-	3.27E+00	-
Diesel (transporting waste paper/km)	[l]	-	-	1.10E-01	-
Diesel (transporting RHH waste/km)	[l]	-	-	1.50E-01	-
Electricity	[kWh]	-	4.40E+00	-	-
Electricity Body	[kWh]	-	2.50E-01	-	-
Electronics	[t]	2.60E-06	-	-	2.60E-06
Ethanol	[t]	1.80E-07	-	-	
Glass	[t]	2.70E-06	-	-	2.70E-06
Glycol	[t]	7.80E-07	-	-	
HDPE	[t]	1.90E-05	-	-	1.90E-05
Iron	[t]	1.20E-04	-	-	1.20E-04
Oil, grease	[t]	2.80E-06	-	-	
Rubber	[t]	2.10E-05	-	-	2.10E-05
Stainless steel	[t]	6.80E-07	-	-	6.80E-07
Steel	[t]	3.40E-04	-	-	3.40E-04
Textile	[t]	2.60E-06	-	-	2.60E-06
Wood	[t]	5.00E-07	-	-	5.00E-07

3.3 Life cycle assessment of waste management systems

The results of six scenarios will be presented in this section. Figure 3 sums up the results from Paper V for Scenarios 1-4, showing the contribution of capital goods to the total impact resulting from the treatment of waste. Capital goods showed high contributions to AE(P), RD and toxic impact categories, and based on this finding capital goods should be included in waste management LCAs. Figure 4 shows the contribution of capital goods used for the collection and transportation of waste. The contributions, especially from the trucks, are high and capital goods should be included when assessing the collection and transportation of waste.

3.3.1 Windrow composting

Capital goods in Scenario 1: Composting of 1 tonne of garden and park waste contributed more than 20% to GW, RD, AE(P), HTc and ET (see Figure 3). The impacts were caused by the production of energy for the production of concrete pavement, transportation of materials and goods and the use of steel for machinery. Impacts from steel for the machinery and their direct effects were caused by the disposal of slag from steel production and the disposal of spoil from coal mining for energy production. The impacts caused by the operation of the composting plant were due primarily to emissions of methane and ammonia from the composting process.

3.3.2 Anaerobic digestion

Capital goods used for anaerobic digestion contributed most to the potential impact on RD and HTc (see Figure 3). The potential impact on both categories was caused by the use of steel and the emissions of heavy metals from the disposal of slag.

From the operation of the anaerobic digester, savings for GW and AC were caused by the substitution of energy produced from biogas. The process-specific emission of methane led to potential impacts on OFv and OFh, while the leaching of nitrate into surface water from the digestate used on land caused an impact on AE(N). Fertilizer substitution produced savings on AE(P) because of avoided emission of phosphorous to water and on HTnc because of savings of zinc from the fertilizer substitution. The impact from zinc on HTnc is very uncertain because of methodological issues with the USEtox characterisation factors for zinc.

The ILCD handbook states a strong need for further research into the CF for zinc (European Commission, 2011).

3.3.3 INCINERATION

Two scenarios were assessed for the functional unit in Scenario 3, the incineration of 1 tonne of residual household waste. Scenario 3a was modelled with high energy recovery efficiency (95%) and Scenario 3b included lower efficiency (29%).

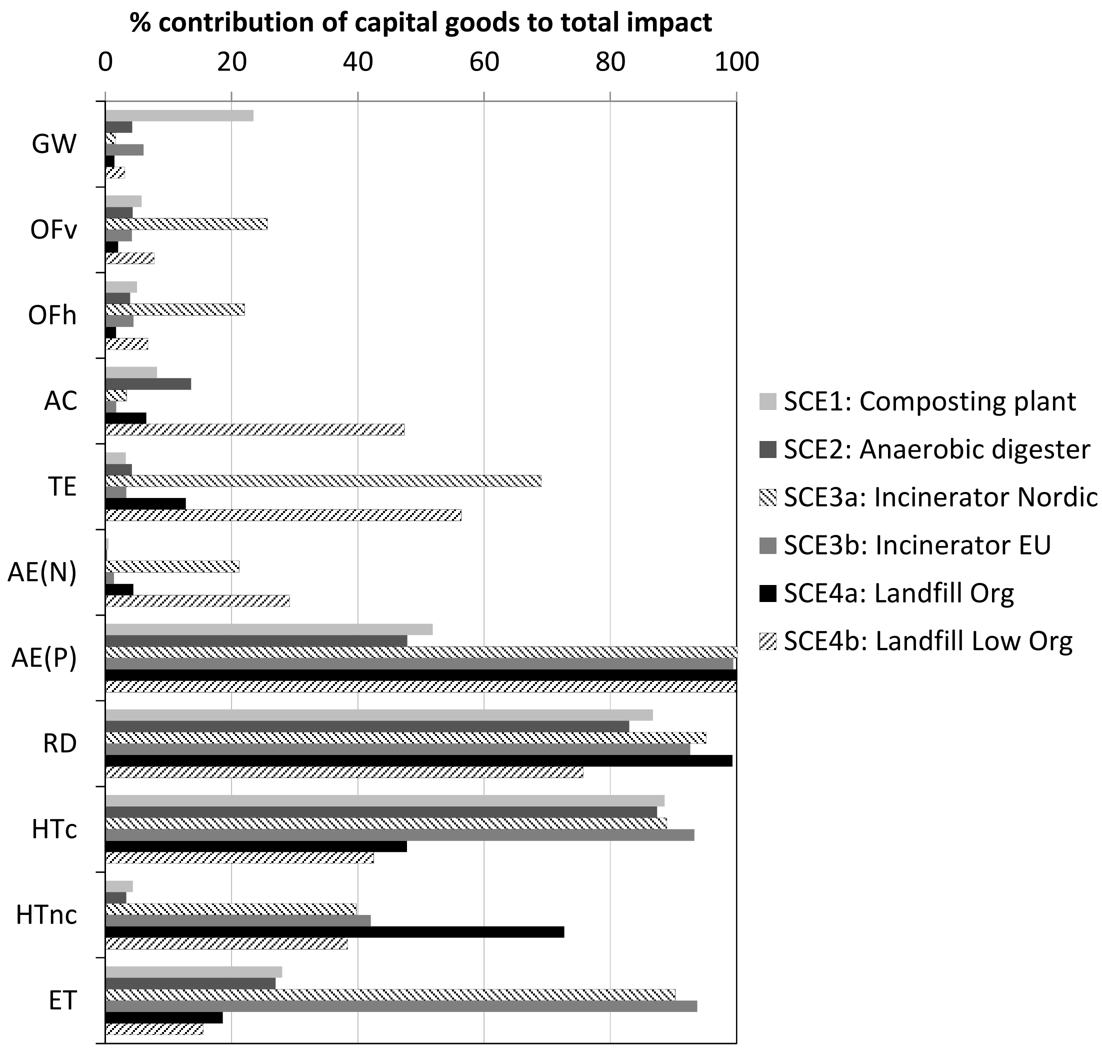

Figure 3: Contribution from capital goods to total impact in Scenarios 1-4. GW: Global Warming, AC: Acidification, TE: Terrestrial Eutrophication, AE(N) and AE(P): Aquatic Eutrophication in N-equivalents and P-equivalents, OFv and OFh: Photochemical Ozone Formation impacts on vegetation and human health, RD: Resource Depletion, HTc and HTnc: Human Toxicity related to cancer and non-cancer related, ET: Ecotoxicity.

Capital goods contributed more than 80% to the total impacts on AE(P), RD, HTc and ET (see Figure 3). The impact on AE(P) and RD was influenced by nickel and steel production, and electricity consumption for the production process also contributed to the impact on AE(P). The production of steel for machinery and the processes related to the production of steel leading to heavy metal emissions into the air and water contributed to impacts on the toxicity categories for capital goods.

Large savings on GW, OFv and OFh in the Nordic scenario were made because of the high plant efficiency and thereby high substitution of heat. Large savings on AC from European Scenario 3b were due to the higher emission of SO_2 from the substituted European electricity rather than the Danish mix used in Scenario 3a. Differences between impacts on TE in Scenarios 3a and 3b were caused by the higher emission of NOx from the European energy mix compared to the Danish model.

3.3.4 Landfilling

Scenario 4 assessed the landfilling of 1 tonne of mixed waste. The waste was mixed household waste with an organic content of around 35%, and this was included in Scenario 4a. Scenario 4b assessed the effects of landfilling 1 tonne of mixed waste with a low organic waste content, in order to represent landfills in countries with small amounts of organic waste going into landfill sites. The capital goods in scenario 4b did not include landfill gas collection or its management.

Figure 3 shows contributions to the impact categories by the capital goods and the operation. Savings on the potential impact on GW and AC by the operation were made as a result of the energy produced from the collected landfill gas substituting fossil energy. The degradation of organic waste and uncollected methane emitted through the top cover were the main causes of potential influences on OFv and OFh.

The effects of capital goods on the toxicity categories were caused by the production of steel for containers, fences and reinforcing concrete tanks, as well as the disposal of slag from recycling the steel. The potential impact on AE(P) was caused by lignite and coal mining and the disposal of tailings.

Results for the assessment of Scenario 4b are presented in Figure 3. Scenario 4b does not include gas collection, which caused higher potential impacts than Scenario 4a, as no energy was recovered.

The transportation of materials for the capital goods contributed considerably to the landfill scenario. These contributions were caused by the large amounts of waste transported to the landfill site compared to the other technologies.

3.3.5 Collection and transportation

Scenarios 5 and 6 assessed collecting and transporting 1 tonne of household waste and 1 tonne of waste paper from public collection points. Capital goods in these scenarios are the bin, cube and truck, and the operation involves collection and transportation.

The impacts caused by capital goods in relation to collection and transportation can be found in Figure 4. The collection truck contributed significantly more than the 240-litre bin and the cube container per tonne of waste. The operation contributed most to the non-toxicity impact categories, while capital goods contributed more to AE(P), RD, HTnc, HTc and ET. The large contribution of capital goods to AE(P) was caused by the choice of European energy input from the Ecoinvent database, which included a wide mix of energy sources, such as lignite mining. The tailings deposited in landfill sites caused high potential impacts on AE(P) for the steel used in the bin, cube and the truck. The potential impact on RD was caused by the resources (iron, nickel) used for steel production. The emission of mercury and chromium from the steel production process caused the potential impacts on toxicity categories.

The collection operation contributed more than transportation to all impact categories. This was due to more starts and stops and higher diesel consumption per tonne of waste. All potential impacts from the operation were caused by emissions from the combustion of diesel in the collection truck. The RD from the operation was caused by the use of crude oil and energy resources for the production of diesel.

3.4 Key results

The inventories for a composting plant, anaerobic digestion plant, incinerator, landfill, bins and truck, presented in Section 3, could be used by LCA practitioners to include capital goods for waste management LCAs. Examples of inventories for all technologies are presented in Papers I-IV.

Life cycle assessments of the technologies were presented to evaluate the importance of including capital goods in waste management LCAs. The results showed a significant amount of importance for Aquatic Eutrophication, Resource

Depletion and toxicity impact categories with effects on human health and ecosystems.

Capital goods influence the results of total impacts stemming from operating a composting plant. The productions of large amounts of gravel and concrete stones, as well as steel for machinery, were the main contributing processes of capital goods in composting.

Concerning anaerobic digestion, capital goods alone do not contribute substantially to Resource Depletion and Human Toxicity (non-carcinogenic) – concrete and steel were used in large amounts, and the production of steel for steel reactors contributed most to the total impacts.

For incineration, two scenarios were assessed. Capital goods should be included when assessing the incineration of waste for both the Nordic and European scenarios, and especially machinery steel and electronics used at the plant should be included in the life cycle assessment.

Capital goods for landfilling are recommended for inclusion in waste LCAs, as large amounts of materials for liner systems need to be transported, thus leading to high contributions. Regardless of the organic content of waste and the need for gas management, capital goods are important.

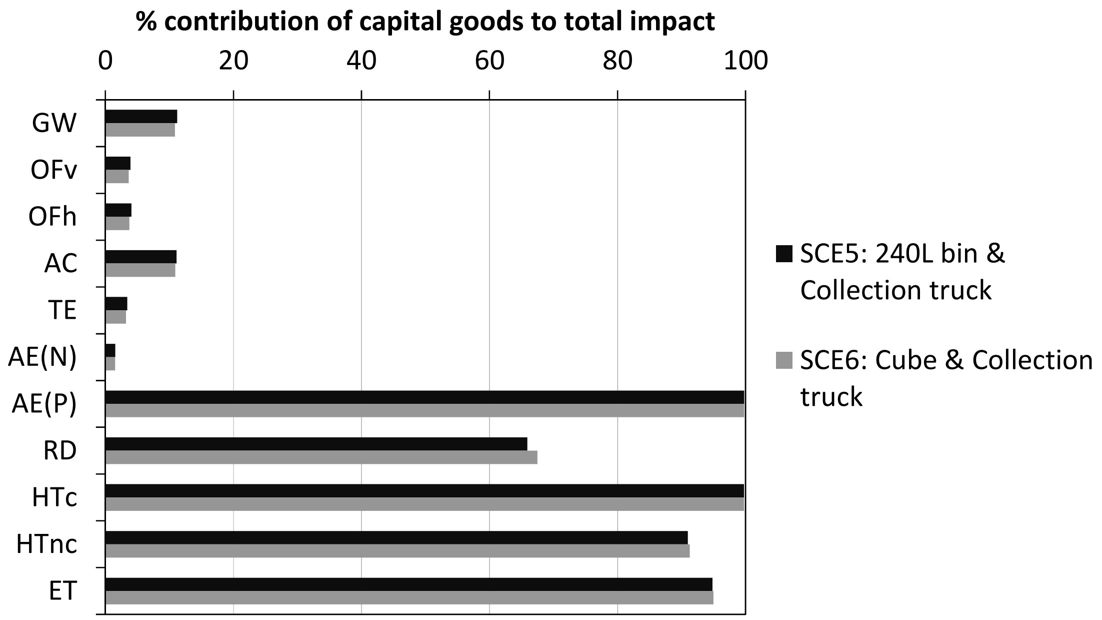

Figure 4: Contribution of capital goods to total impact from full LCA of Scenario 5 and 6 concerning collection and transportation.

Impacts caused by the collection and transportation system are small for most impact categories compared to waste management technologies. The electricity mix and the choice of steel used for the production of rucks led to high impacts on AE(P), RD and HTc. The inclusion of capital goods for collection and transportation in the full scenario of a waste treatment system should be considered.

Capital goods do contribute to the total impacts of waste management systems. The picture is diverse, however, since not all impact categories are affected by capital goods, though it is recommended to include them in any research. The inclusion of capital goods could depend on the impact categories under examination in a study. If Resource Depletion and toxicity impacts are prioritised, capital goods should be included. The depletion of resources will always matter when assessing capital goods, as the share saved from recycling goods will never be higher than the impacts from producing the goods in the first place, in addition to the impacts from recycling and transportation. Studies focusing on impacts on Global Warming do not need to include capital goods – this kind of study will reveal that the environmental loads from energy consumption during the lifetime of capital goods are insignificant compared to the energy produced by waste management systems.

4 EXTERNAL MATERIAL DATABASES

This chapter describes how primary and secondary material production processes are represented in available databases and then presents variations between datasets. The purpose of this chapter is also to highlight the many obstacles in waste management LCA faced by practitioners performing recycling system LCAs.

The Waste and Recovery Action Programme published a far-reaching review in 2006 of LCA studies of recycling versus incineration and landfilling (WRAP, 2006). The review showed variations in the results of the studies examined, but it did not look into the inventories behind the LCAs. The WRAP study included LCAs for the treatment of waste paper, glass, plastic, aluminium, steel, wood and aggregates.

A smaller study was carried out by Merrild et al. (2008) on waste paper management, and large variations were seen for CO_2 emissions from reprocessing and virgin production of paper from single datasets.

To evaluate the proportions of variations seen from previous studies, 366 datasets for materials were gathered and evaluated (Paper VI).

4.1 DATABASES

Several external databases are available today for LCA practitioners, some of which include data on primary and secondary material production. To undertake an overview of the available data, 26 data sources were included in the evaluation, and these are listed in Table 9. In all, 46 potential data sources were discarded because of closed websites, language issues or payment required to access the data.

At total of 366 datasets for 14 materials from 1980-2010 were collected from databases, reports and papers. For primary production, 270 datasets were found and 96 datasets for secondary production. The materials assessed were glass, paper, cardboard, corrugated board, newsprint, steel, aluminium and plastics (HDPE, LDPE, LLDPE, PP, PVC and PS).

Documentation and background information for the data turned out to be more scarce than expected. The guidelines given by ISO standard 14044 (ISO, 2006) on how to perform LCAs and how to document inventories are seldom followed. In many cases, the age and origin of data were also hard to find. Data without transparent background information were included in the evaluation, as these can be used by LCA practitioners who may not be aware of a surfeit of information.

CO_2 was found to be a good indicator parameter for energy consumption in the processes. Energy-related processes are often well-represented in inventory data, and CO_2 can be a measure of the amount of fuel used. The emission of CO_2 does not influence all impact categories and the evaluation does not cover other LCA impact categories other than Global Warming.

Table 9: List of databases, reports and papers and how the data were accessed (Paper VI).

#	Reference	Access
1	Aluminium Association (2010)	Free report
2	Arena et al. (2004)	Free paper
3	Avfall Norge (2009)	Free report
4	BUWAL(1990)	Paid license needed
5	Corrugated Packaging Alliance (2009)	Free report
6	EASEWASTE (2005)	Training course
7	Ecoinvent (2013)	Paid license needed, or license for Simapro or Gabi
8	ELCD (2012)	Free download of data from homepage
9	ETH-ESU (1996)	Paid license needed for Simapro
10	EUROFER (2000)	Paid license needed for GaBi or see ELCD homepage
11	European Commission (2001)	Free report
12	EAA (2005)	Paid license needed for GaBi
13	Franklin USA (1995)	Paid license needed for Simapro
14	Gemis (1990)	Download from homepage
15	IDEMAT (2001)	Paid license needed for Simapro
16	IFEU (2009)	Free report
17	Industry data 2.0 (2013)	Paid license needed for Simapro
18	International Aluminium Institute (2007)	Free report
19	Interseroh (2007)	Free report
20	PlasticEurope (2005)	Via LCA tools or free download from homepage
21	US EPA (1998)	Free report
22	US EPA (2003)	Free report
23	USLCI (2013)	Free download from homepage
24	WorldSteel (2007)	Paid license needed for GaBi
25	WRAP (2008)	Free report
26	Återvinningsindustrierna (2002)	Free report

4.2 Evaluation of data

Branch organisations and industries report on energy optimisation in the production of paper and steel (Stora Enso, 2011; IP, 2010; CEPI, 2011; World steel association, 2012). Emissions of CO_2 from production of materials are therefore expected to decrease over time – a notion that was expected to be visible in the databases. The first finding of note discovered from the collected data was that emissions have not decreased over time and large variations between data for the same material are evident for all evaluated materials.

In this section the data found for office paper, HDPE, steel and aluminium will be presented. The full evaluation can be found in Paper VI.

4.2.1 Office paper

Datasets found for the production of office paper showed large variations. Each database seemed to have its own trends, as highlighted in Figure 5. The 11 datasets found for secondary production were in the range of 0.38-1.56 kg CO_2-eq/kg material. Primary production showed an even larger interval of 0.04-4.08 kg CO_2-eq/kg material from 26 datasets.

The dataset "Printing Paper, incl. alternative fuel" in Figure 5 includes a consequential system expansion leading to a higher emission of CO_2. The assumption was that wood was used for primary paper production and could therefore not be used as fuel. Natural gas is used instead of wood, and this additional combustion leads to the higher emission of CO_2.

It was not possible to find either background information on or the geographical origin of low emissions for source 14 (GEMIS database).

The datasets from source 21 (USEPA, 1998) treated paper as a biogenic fuel and did not include CO_2 in any calculations. This could be the reason for emissions lower than the other data presented. The use of energy is crucial for the comparison for CO_2 emissions; if the energy mix is not defined, it is not possible to trace emissions.

Obsolete links to data reports are one of the challenges LCA practitioners meet when trying to find data. When the background information cannot be found, it is not possible to find the specifications, such as for "Printing Paper, incl. alternative fuel" including the consequential approach. In this case the name gives some additional information, but from the name it is not possible to get an explanation on any thoughts behind system expansion.

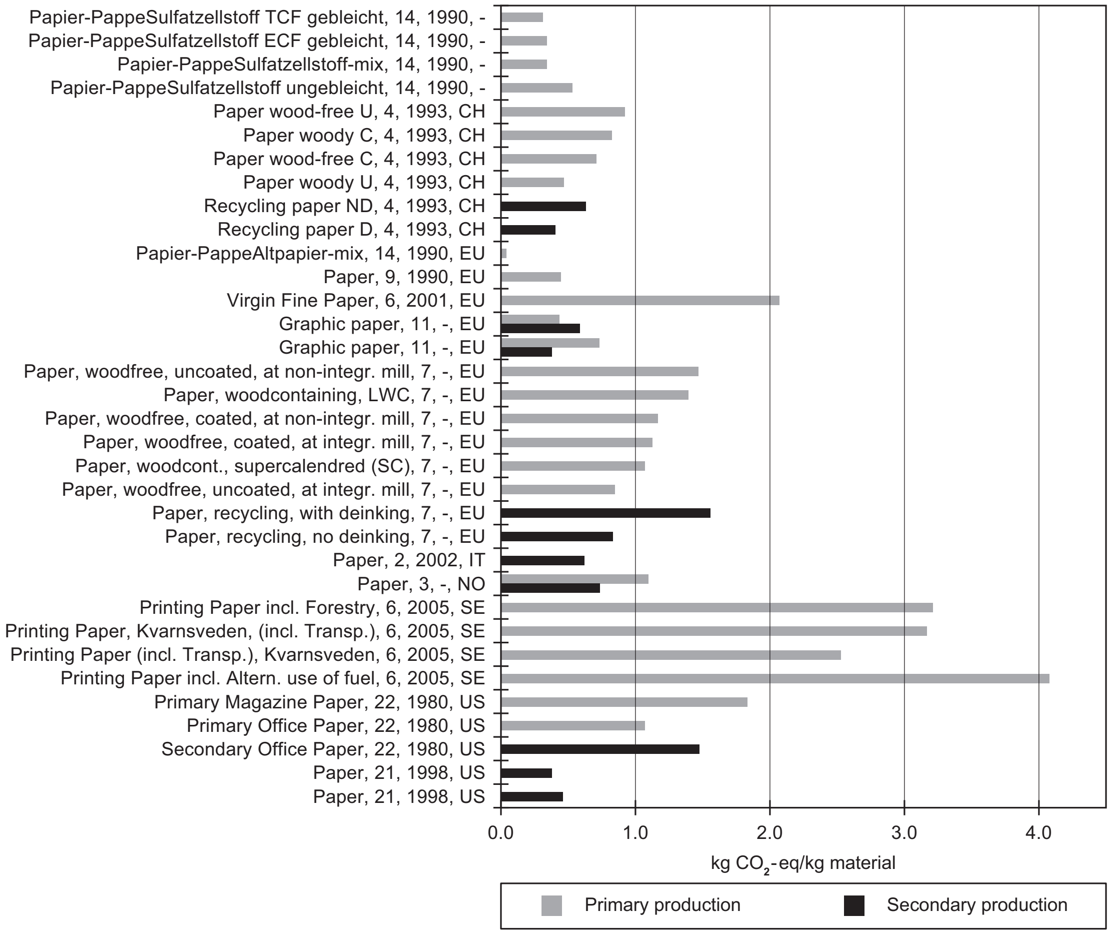

Figure 5: Emission of CO_2-eq from the primary and secondary production of office paper (Paper VI). Numbers in names refer to sources in Table 9. “-”: No data found.

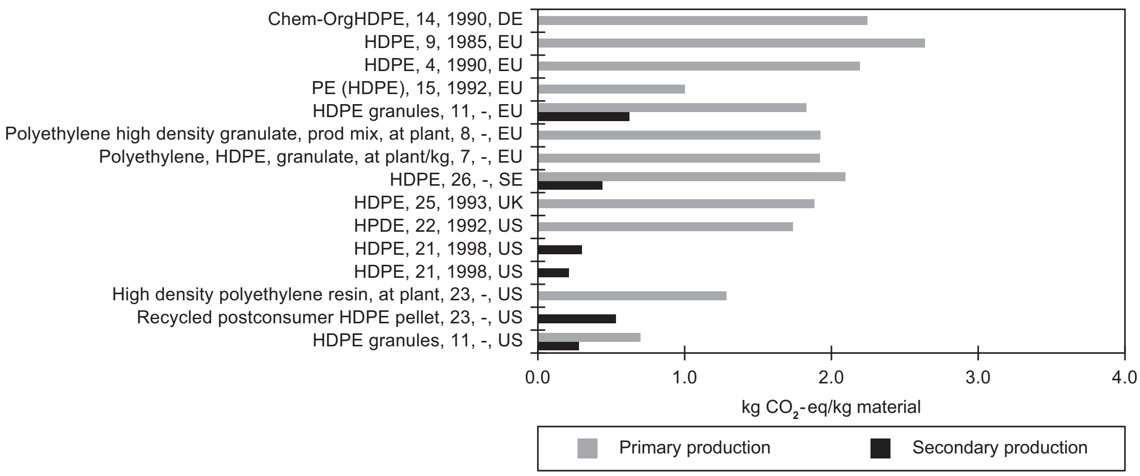

Figure 6: Emission of CO_2-eq from the primary and secondary production of high density polyethylene (Paper VI). Numbers in names refer to sources in Table 9. “-”: No data found.

4.2.2 High density polyethylene

Data for the production of HDPE were primarily from the 1990s, and some datasets did not state their age (see Figure 6). It is difficult for the LCA practitioner to determine if any technology upgrade happened after the data were produced.

Plastic Europe provided data for 7-Ecoinvent and 8-ELCD, and the data were equal even though the ELCD dataset includes "production mix" in the name. The process documentation does not mention any input of secondary material.

Data from 15-IDEMAT were lower but it was not possible to find any explanation for this result because the reports were no longer available.

Empty "dummy" processes cause lower emissions from the 23-USLCI. Users need to fill in the processes by themselves for electricity and some transportation processes. The datasets from USLCI on HDPE are considered incomplete but were nevertheless included in the study to show the challenges for LCA practitioners.

No background information, inconsistent information, old data or half datasets were the challenges for HDPE datasets.

4.2.3 Steel

The production of steel was better represented than the other materials in the databases and sources found. In all, 41 datasets were included for primary steel with a range of 0.4-7.03 kg CO_2-eq/kg steel. For secondary production 11 processes were found and the emissions were in the range of 0.02-2.94 kg CO_2-eq/kg steel (Figure 7).

The GEMIS processes from Czechoslovakia and China presented high CO_2 emissions but did not include any background information. The low emissions from the German GEMIS data included only processing and not mining activities.

The "Steel (sec)" process from 15-IDEMAT represents emissions from the electro furnace production of 100% secondary steel and the emissions are high compared to the other secondary steel processes. It was not possible to find adequate background information for the dataset from IDEMAT.

For the steel processes in this research, large variations were found between the data. Because the LCA results can be highly dependent on single datasets, it is necessary to check all details about the processes involved.

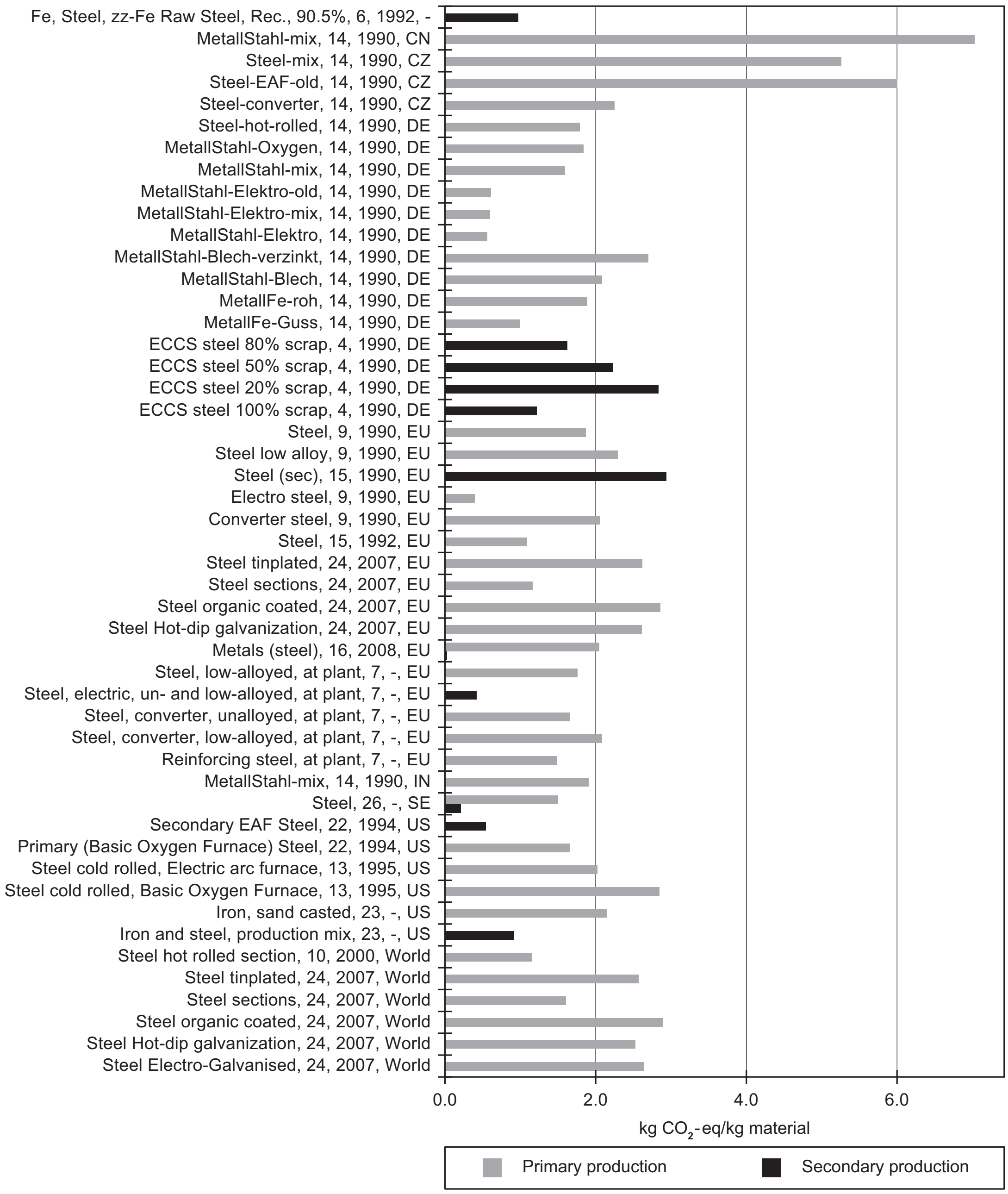

Figure 7: Emission of CO_2-eq from the primary and secondary production of steel (Paper VI). Numbers in names refer to sources in Table 9. "-": No data found.

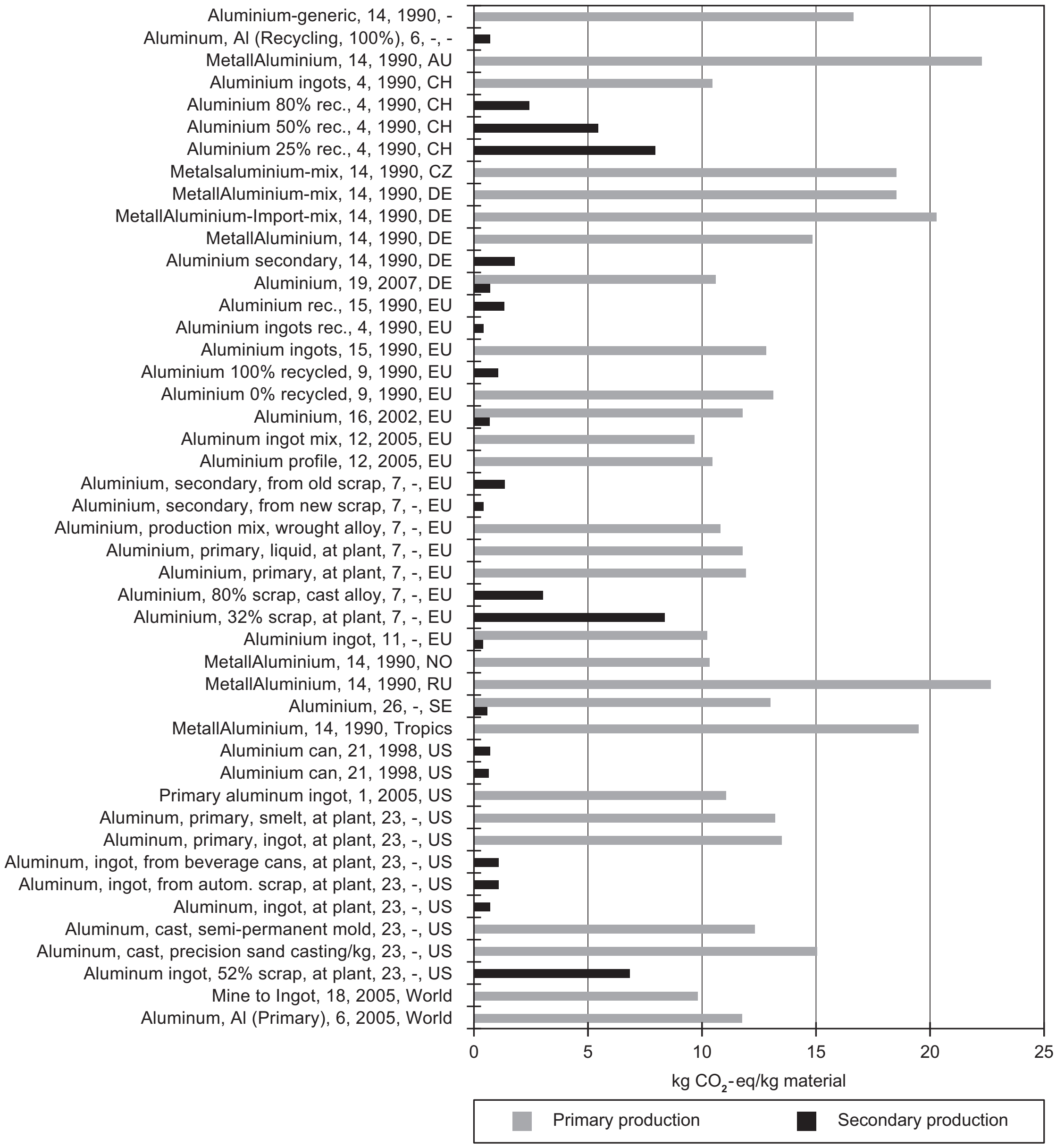

Figure 8: Emission of CO_2-eq from the primary and secondary production of aluminium (Paper VI). Numbers in names refer to sources in Table 9. “-”: No data found.

4.2.4 ALUMINIUM

For secondary aluminium production, data for the emission of CO_2/kg material was in the range of 0.40-8.37 kg CO_2-eq/kg secondary aluminium (see Figure 8). Primary production led to higher emissions at 9.67-22.68 kg CO_2-eq/kg primary aluminium. The high emissions from secondary production were seen for datasets including production mix, meaning a mix of primary and secondary aluminium.

Aluminium production is an energy intensive process and the energy mix used is therefore very important for the processes. The numbers are equal for the European data and American data concerning primary aluminium production. The differences between primary aluminium production and primary aluminium goods (sheets, foil and cans) were not significant, which could be due to high energy consumption during the production of the material, whereas the production of the good is less energy intensive.

The 14-GEMIS data included the same process of producing aluminium and included different energy mixes dependent on geographical relevance. As an example, the dataset from Norway includes 99.5% hydropower whereas the Australian sample includes 77.6% coal, 12.6% gas, 1.3% oil and the remainder hydropower and waste. This causes large variations between the datasets found in 14-GEMIS.

4.3 KEY RESULTS

The key results from the evaluations were that large variations were present, the challenges of choosing data for recycling systems are manifold and background information is often inadequate or non-existent.

Figure 9 shows the highest and lowest values found, the mean value and standard deviation for the primary and secondary production processes for all evaluated materials. Data were not available for the secondary production of LLDPE, PP and PVC. The standard deviations turned out to be high, due to large variations in the data. The differences between the highest and lowest estimated CO_2 emission from the primary production of HDPE and glass were 443% and 452%, respectively. For steel and aluminium the differences were 1,761% and 235%, respectively.

Variations in Figure 9 occur because of different energy systems, different modelling approaches and a lack of data in inventories. The averages presented in Figure 9 can be used as a guideline for the CO_2 emissions, but not as a single number for inclusion in inventories. Each evaluated dataset represents a specific process with a specific background which should be considered for LCA studies. The numbers in Figure 9 show the benefits for recycling systems if the average figures for primary and secondary production are used together for LCAs. The overlapping of the ranges shown in Figure 9 demonstrates the importance of choosing representative datasets, as the benefit will go to one or the other system. Some databases couple datasets, so LCA practitioners still need to make sure the processes are relevant for the actual study.

LCA practitioners should strive to find data representing the actual processes being modelled. Some branch organisations (e.g. World Steel and Plastic Europe) provide data and reviews of their datasets, which represent actual markets and can be considered ‘good’ data. Lacking knowledge on the modelled processes will force LCA practitioners to use the best available data. Background information for generic datasets should follow ISO standards and as a minimum be clear about the origin and age of the data. Generic data can be used for generic studies or when no better data is available, but only if it is grouped with LCA results.

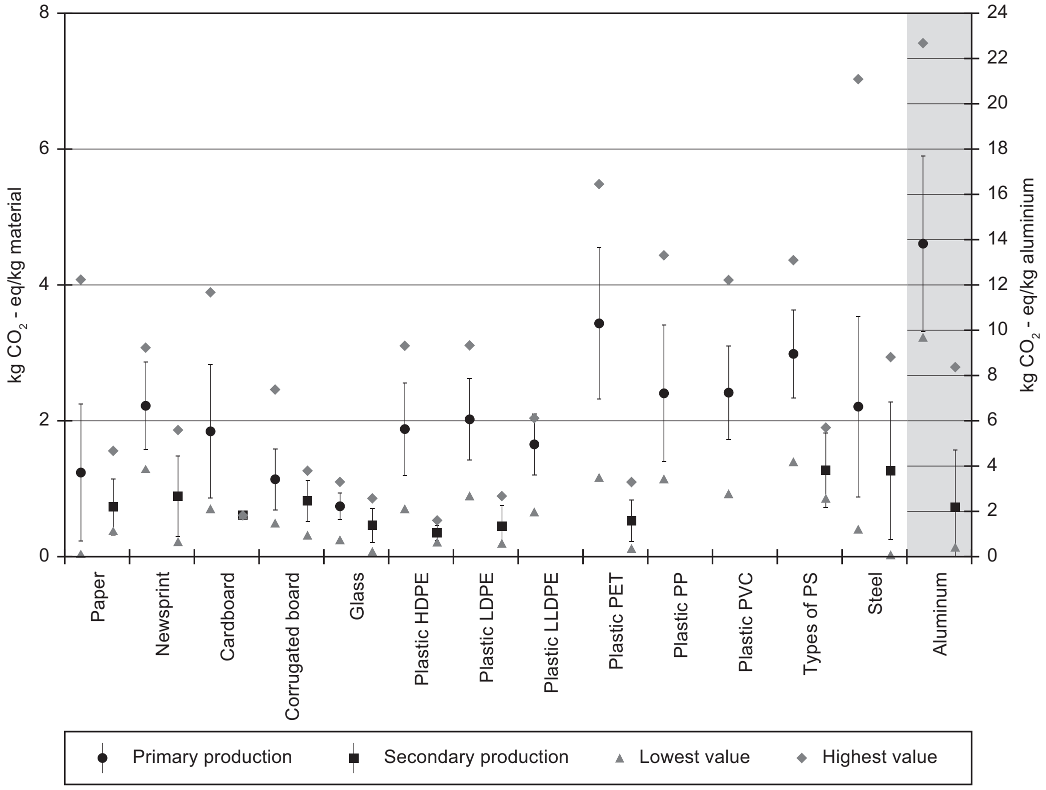

Figure 9: Highest and lowest value, mean values of all data found for each material and standard deviation. No data found for secondary LLDPE, PP and PVC (Paper VI).

5 DISCUSSION

5.1 CAPITAL GOODS FOR WASTE MANAGEMENT SYSTEMS

Including capital goods in waste LCAs is recommended however, their relative importance depends on the observed impact categories. If impacts on aquatic eutrophication, resource depletion and toxicity are prioritised, then capital goods should be included. The choice of including capital goods could therefore depend on the impact categories within the study. The sizeable influence of capital goods on resource depletion was due to the impact from recycling processes for high value products such as metals. The impacts from recycling are lower than from the virgin production of the same materials, but they are nevertheless significant. Overall the net impact will always result in a load to the environment for resource depletion, as a result of the virgin production, the recycling and treatment of materials, and the avoided impacts from recovered materials.

The main parts of the capital goods were quantified, but data for related systems could be improved to perform better LCAs. The lack of data was especially observed regarding:

- Data on disposal processes for demolition waste. A few datasets are available, but more detailed data regarding routing of waste fractions and better documentation is needed.
- Data on production and disposal treatment of electronic components for incineration plants. For this study only a few datasets were found and they did not include information on the individual electronic parts.
- Information about lifetimes of the waste treatment technologies. Expert estimated lifetimes were used and sensitivity analysis showed how the lifetime influences the amount of maintenance and impacts per tonne of waste treated.
- Data for all energy consumptions (electricity, heat, diesel etc.) during construction and demolition. These data were only quantified for some of the technologies.
- Data for capital goods of distribution networks. District heating systems and electricity networks were not included in the study.

The lifetimes of capital goods were deduced by experienced consultants who had built actual plants. Assessments of variations of the lifetimes were performed in

Papers I-IV, to observe their influence on the impacts of the construction of capital goods. A longer lifetime for the incineration plant, composting plant and anaerobic digester would decrease the impacts per tonne of waste. The additional impacts from maintenance would be insignificant due to the higher amount of waste determining the impacts per tonne of waste. A longer aftercare period for the landfill would increase the impacts caused by capital goods. Since the amount of waste would not change, but more maintenance would be needed for gas and leachate management, the impacts per tonne of waste would be higher.

Energy consumption for the construction and demolition phases was quantified for the landfill and the incinerator. The results showed important impacts for landfill sites due to the large amounts of materials being moved at the location. For the incinerator, impacts were smaller, but the relevance of the data was uncertain, since they represented only one source of information. The energy for construction is estimated to be of minor importance compared to the savings from the large amounts of energy produced during the operation phase. However, diesel and heat consumption at the site were not possible to quantify, and these would increase the environmental impacts related to capital goods.

Energy systems and transportation were found dominating for the impacts of capital goods. If the system being assessed produces energy or fuel (incinerator, biogas, landfill), the impacts on GW caused by capital goods becomes insignificant, due to the savings of energy from fossil fuel.

The choice of inventory data was crucial for the results as emissions and resource consumption can vary considerably between datasets. It is therefore important to assess the sensitivity of the results by testing alternative options if the actual process data are not known.

5.2 DATASETS FOR MATERIAL PRODUCTION

Choosing relevant inventory data for a LCA study is often hard for the LCA practitioner as lack of transparency and background information makes it difficult to evaluate the quality of data. Guidelines on how to document inventory data are presented by ISO standard 14044 (ISO, 2006), but the work presented in Paper VI showed that the guidelines are seldom followed and even large commercial databases do not follow the standard. Large variations on emission of CO_2 were observed for all materials in Paper VI. Common weaknesses found in the databases were: 1) empty “dummy” processes included in inventories, 2) missing background information, 3) the inclusion of wider systems than explained in the name of the dataset, 4) lack of clarity regarding input material, i.e. mix of secondary and primary material, and 5) absence of time references.

The use of proper data for marginal energy and material production is crucial when undertaking consequential LCAs. Modelling consequential systems requires a clear description of the marginal datasets employed, in order to help the reader to understand any assumptions made, for example the consequences of introducing a new system. The importance of this choice is illustrated by McMillan and Keoleian (2009) through an aluminium case study. They described how the European aluminium production is less energy intensive than the Asian production, and the majority of the growth in aluminium production is taking place in Asia (McMillan and Keoleian, 2009). They conclude that LCAs of aluminium recycling should include the avoided primary production in Asia, by using Asian inventories or/and Asian energy data. In relation to that, Paper VI presented the greatest difference in emissions of CO_2 was found between non-fossil energy systems, such as those found in Norway (99% hydropower) compared to 91 % coal-based energy in Poland (EEA, 2007). Information about country specific energy data and types of fuels is thereby important for the inventories used by the LCA practitioners.

Finally, proper maintenance and updates of databases are necessary. The amount of currently available data is huge, so performing quality checks on all inventories is a big challenge. It is not likely that this will be achieved, so it is important for LCA practitioners to be aware of the pitfalls of choosing LCI datasets. Following the standard would provide better background information for the practitioners, who are not familiar with all processes necessary for one study. Some branch organisations provide very useful data, which represent their industry and deliver reviews on the production on which they are experts. For example, Plastic Europe has contributed to a great increase in the data consistency of plastic production in Europe. Consensus within other industries providing data for LCA practitioners would make better representation in LCAs of the industries and thereby better LCA studies.

6 CONCLUSIONS AND RECOMMENDATIONS

The goal of this PhD was to assess the importance of technical externalities for LCAs of waste management systems.

The first aim of this PhD project was to verify/contradict the assumption that environmental impacts from capital goods can be neglected in comparison with other impacts in a waste management system. Capital goods were quantified and presented in inventories for four major technologies: windrow composting, anaerobic digestion, incineration and landfilling. Capital goods in terms of bins, containers and trucks used for collecting and transporting waste were also quantified.

Life cycle assessments were performed to evaluate the importance of capital goods in comparison to the operation of waste management systems. The results were highly dependent on the quality of the inventory data used and on wider knowledge about the included processes. Using best available inventory data for capital goods showed that they should be included in LCAs. Capital goods contributed especially to aquatic eutrophication, resource depletion and toxicity impacts on human health and ecosystems.

The second aim was to evaluate the quality of data for the primary and secondary production of materials in external databases. The materials under the spotlight were from the municipal waste stream: paper, newsprint, cardboard, corrugated board, plastics (HDPE, LDPE, LLDPE, PET, PS and PVC), glass, steel and aluminum.

The quality of data for the primary and secondary production of materials was evaluated by collecting 366 datasets, representing 14 materials from 26 data sources. Less than one quarter of the datasets evaluated represented secondary materials, highlighting a severe lack of such production datasets.

The study presented in Paper VI showed that energy systems are central to the quantification of impacts and are thereby important to define. There is a critical lack of background information for available datasets, which makes the energy systems included in the datasets difficult to identify. More transparency is therefore needed in databases, to describe the background of inventory data and make it possible to assess the quality of data. Following ISO standard 14044 increase transparency, while consensus in industries and branch organisations would provide better data for LCA practitioners.

In conclusion, technical externalities for waste management LCAs are important. Both capital goods and material production systems have a significant influence on how an LCA is performed, as well as on the final results. When technical externalities are included it is important that background information is adequate, since the quality of the data will determine the quality of the results.

7 PERSPECTIVES

The present study showed the importance of including capital goods and expanding the system boundaries of waste management LCAs. LCA practitioners can use the data presented in future studies to include capital goods in LCAs.

Doing that, more data on capital goods technologies would be required to assess other waste management systems. Technologies quantified in further studies could be:

- Pyrolysis and gasification
- Enclosed anaerobic digestion
- Combined mechanical-biological treatment
- Waste sorting plants
- Distribution systems for heating and electricity
- Other plant types than the ones included in this study, especially for the anaerobic digester.

Data quantified in this study for the capital goods represents plants and technologies that are relevant for conditions in developed countries with proper infrastructure and well managed waste treatment systems. Country specific plants could be quantified, to represent particular plants or plants in developing countries.

Improved data on recycling processes are needed, for both the recycling of demolition waste of capital goods and for municipal solid waste fractions. The better representation of recycling processes would improve the quality of product systems as well as waste management systems LCAs. Waste management industry should provide these data.

An extended evaluation combining economical capital costs and environmental impacts would be useful for waste managers to choose the best option in a holistic perspective. By combining assessment methods the basis of decision support would be stronger.

EDIP2003 and USEtox were the chosen life cycle assessment methods, used in this study and it is believed that using other methodologies, would give equal results. However it would be interesting to investigate the share of impacts from capital goods with different methods.

For the relatively new method USEtox some issues of further research needs were defined for the characterization factors, by the ILCD handbook. This and other developments of characterization factors e.g. the time specific characterization factors will be interesting to apply for future assessments of waste management systems and capital goods.

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PAPERS

The following papers are included in the thesis:

I Brogaard, L.K., Christensen, T.H. (2012) Quantifying capital goods for collection and transport of waste, Waste Management and Research, Volume 30, Issue 12, pp. 1243-1250

II Brogaard, L.K., Stentsøe, S., Willumsen, H.C., Christensen, T.H. (2013) Quantifying capital goods for waste landfilling, *Journal of Waste Management and Research*, Volume 31, Issue 6, pp. 585-598

III Brogaard, L.K., Riber, C., Christensen, T.H. (2013) Quantifying capital goods for waste incineration, *Journal of Waste Management*, Volume 33, Issue 6, Page 1390–1396

IV Brogaard, L.K., Petersen, P.H., Nielsen P.D., Christensen, T.H. (2013) Quantifying capital goods for biological treatment of organic waste, in review for the *Journal of Waste Management*

V Brogaard, L.K., Christensen, T.H. (2013) Life cycle assessment of capital goods for waste management systems, in manuscript for *Journal of Waste Management*

VI Brogaard, L.K., Damgaard, A., Jensen M., Barlaz, M., Christensen, T.H. (2013) Evaluation of life cycle inventory data for recycling systems, in manuscript for *Journal of Resources, Conservation and Recycling*

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from:

DTU Environment
Technical University of Denmark
Miljoevej, Building 113
2800 Kgs. Lyngby
Denmark

reception@env.dtu.dk

The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within four sections:
Water Resources Engineering, Urban Water Engineering,
Residual Resource Engineering and Environmental Chemistry & Microbiology.

The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

DTU Environment
Department of Environmental Engineering
Technical University of Denmark

Miljoevej, building 113
2800 Kgs. Lyngby
Denmark

Phone: +45 4525 1600
Fax: +45 4593 2850
e-mail: reception@env.dtu.dk
www.env.dtu.dk